

A Novel Adaptive Structural Impedance Control Approach to Suppress Aircraft Vibration and Noise

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ABSTRACT

Significant levels of undesired vibration and noise are inherent in transport and combat vehicles, particularly in helicopters and propeller aircraft. Therefore, it is important to investigate techniques that reduce vibration and noise in the cabin to improve habitability, effectiveness, and safety for passengers. In addition, continuous exposure may lead to long-term physiological effects. In contrast to passive approaches, active techniques have the potential to suppress low frequency vibration and noise over a broadband of frequencies. Various smart structure based techniques using active materials have been studied for vibration and noise suppression applications. These include active helicopters blades, variable twist propeller blades, adaptive damper, etc. Use of these techniques promises vast improvements in vibration and noise levels. However, full-scale implementations of these techniques have been hindered by electromechanical limitations of active materials.

The Smart Spring is a novel approach to control combinations of impedance properties of a structure, such as stiffness, damping, and effective mass. It uses stacked piezoceramic actuators to adaptively vary structural impedance at strategic locations to suppress mechanical vibration. The Smart Spring is a versatile approach that can be implemented in a variety of applications. For example, an adaptive Smart Spring mount can be used to reduce vibration on vehicle seats, mitigate vibratory loads transmitted from engines, or suppress rotor vibration in helicopters. It is an unique concept that overcomes some of the difficulties encountered with other piezoceramic based vibration control approaches. Extensive experiments have demonstrated the ability of the Smart Spring to control structural impedance properties in an adaptive manner to suppress mechanical vibration. Wind tunnel tests have verified the ability of the Smart Spring to suppress both the vibratory displacement as well as the reaction force under unsteady excitation of a helicopter rotor blade.

1.0 INTRODUCTION

Undesirable vibration is inherent in mechanical systems such as combat and transport vehicles but particularly high vibratory levels exist in helicopters and propeller aircraft. The main sources of vibration in these aircraft include harmonic vibrations induced by propeller or rotor, engine and gearbox operation, and structural excitations caused by unsteady aerodynamics. The vibration energy transferred throughout the aircraft structure not only leads to fatigue damage of expensive components and higher maintenance costs but also create a severe environment for passengers and aircrew. In the short-term, the mechanical vibration transmitted to the human body increases fatigue, degrades comfort, interferes with effective performance, and influences operational safety [1]. In addition, continuous exposure to repetitive vibrations transferred through the helicopter seats have known to cause damaging effects on the spine and neck of the aircrew leading to long-term occupational health issues [2].

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Mechanical vibration also leads to structure-borne noise, which is a major contributor to the overall noise level in vehicles. In contrast to the airborne-noise which radiates directly from the source, structure-borne noise is generated as the fuselage and surrounding panels are excited by vibration transmitted from engines, rotors, etc. The short-term effects of excessive human exposure to acoustic energy include, annoyance, degradation of voice communication and nausea [3]. More importantly, the long-term exposure to high noise leads to hearing loss and modification of physiological functions within major organs [2]. These irreversible effects on human body due to noise and vibration are shown to manifest themselves by repeated exposure and passage of time. Therefore, reduction in vibration and noise in aircraft is important not only to improve habitability of the vehicle but also to mitigate long-term physiological effects on aircrew and passengers.

Passive techniques such as insulators, stiffeners, dampers, and isolators are currently being used in aircraft to provide moderate reduction in noise and vibration. These passive techniques are successful only in reducing vibration and noise transmission in mid and high frequency ranges [2]. However, the primary disturbance frequencies in propeller aircraft and helicopters are related to the blade passage frequency of the rotor, which is generally in the order of 100Hz. At such low frequencies, it is difficult to reduce the passage of noise into the cabin interior through the use of passive approaches such as acoustic insulation due to the long wavelength associated with low frequency noise [4]. In addition, passive approaches incur significant weight penalties and they are generally effective only in a narrow frequency band. In contrast, active approaches can be used in an effective manner to suppress low frequency vibration and structure-borne noise significantly over a broadband of frequencies [5]. More importantly, the adaptability of active systems enable optimization of the system performance due to changes in flight condition, vehicle configuration, weight of the cargo, weight of the crew, etc. In the last decade, technologies based on smart structures approaches using active material actuators and sensors have become an enabler that cuts across traditional boundaries in material science and mechanical engineering. Active materials can be directly embedded into the vehicle structural design or smart systems can be added to structures to perform many functions, such as actuation, sensing or control. Active vibration and noise control is one of the areas that can exploit this emerging smart structures technology to its full extent in order to improve habitability in crew and passenger quarters of aircraft. The actuators in a smart system are driven by a real-time controller to mitigate the unwanted vibration or acoustic field measured by sensors. Several research programs based on smart structures concepts have been conducted to demonstrate potential improvements in vibration as well as noise in aircraft.

2.0 SMART STRUCTURES FOR NOISE AND VIBRATION APPLICATIONS

Various smart structures techniques using a variety of active materials have been studied for aircraft vibration and noise suppression applications. Some of the widely used active materials include, piezoceramic (PZT), shape memory alloys (SMA), magnetorheological (MR) and electrorheological (ER) fluids [6]. Each active material has unique characteristics and a few of the most advanced implementations are summarized below.

2.1 Piezoelectric Material

Piezoelectric (PZT) material is one of the most widely used active materials with inherent electrical and mechanical coupling characteristics. The stiffness of PZT is of the order of 70GPa. Therefore, a deformation caused by an electric field results in a significant mechanical force [7]. The advantages of piezoceramic material are the high bandwidth and the ability to generate large forces necessary for structural actuation. However, the major barrier for application is the low stroke capability, which is less than 0.1% [8]. This limited displacement often requires complex displacement amplifications or application of high voltages [9].

2.1.1 Trailing Edge Flap for Helicopter Blades

One of the smart structures concepts in the advanced development phase is a trailing edge flap powered by a stacked piezoceramic actuator embedded in a helicopter blade to suppress rotor vibration. The system is designed to achieve 80% reduction in airframe vibration and 10dB reduction in blade vortex interaction noise [10]. The trailing edge flap actuator embedded in the blade cavity uses a complex displacement amplification device known as the X-Frame shown in Figure 1(a) to generate sufficient displacement with high forces to counteract the vibratory forces on the blade. The actuator hardware shown in Figure 1(b) contains two parallel PZT stacks operating in a push-pull mode together with the X-Frame mechanism [11]. Laboratory tests have shown a total stroke amplification of 10:1 under simulated loading conditions. A full-scale X-Frame actuator is being implemented to drive a 1m discrete trailing edge flap on a 4m helicopter blade with a 25cm chord. The flight hardware implementing this concept for a MD-900 rotor blade has successfully concluded whirl tower tests as shown in Figure 1(c) [12]. This trailing edge blade flap system for rotor vibration control is scheduled for a flight demonstration in the near future.

2.1.2 Integral Twist Actuation Blades for Helicopter Rotor Vibration Control

In contrast to a discrete actuator such as the trailing edge flap, the integral actuation concept uses distributed actuators along the blade span, as shown in Figure 2, to obtain a smooth continuous structural deformation. The distributed actuator system embedded within the blade skin is designed to twist the composite structure to vary the angle-of-attack in order to counteract rotor vibration [13]. For this application, the structural actuator system is required to be conformable and flexible to facilitate seamless integration directly into the blade spar laminate as active plies within the composite. Therefore, the actuator system consists of continuous piezoceramic fibres aligned in an epoxy matrix [14]. These piezoceramic fibres with high stiffness provide the actuation authority and the polymer matrix improves the toughness properties of the actuator system [15]. A fibre actuator embedded 1/6-scale, Mach-scaled, CH-47D blade showed promising vibration suppression performance in hover tests [16]. A set of Froude-scale blades tested in heavy gas wind tunnels to simulate Mach-scale rotor loads demonstrated the ability of the fibre actuators to withstand considerably higher mechanical loads without catastrophic failure while providing sufficient actuation [17]. A full-scale integral twist rotor is currently being designed and tests conducted on a full-scale blade section incorporating piezoceramic fibre actuators validated the unique manufacturing approach required for implementation [18].

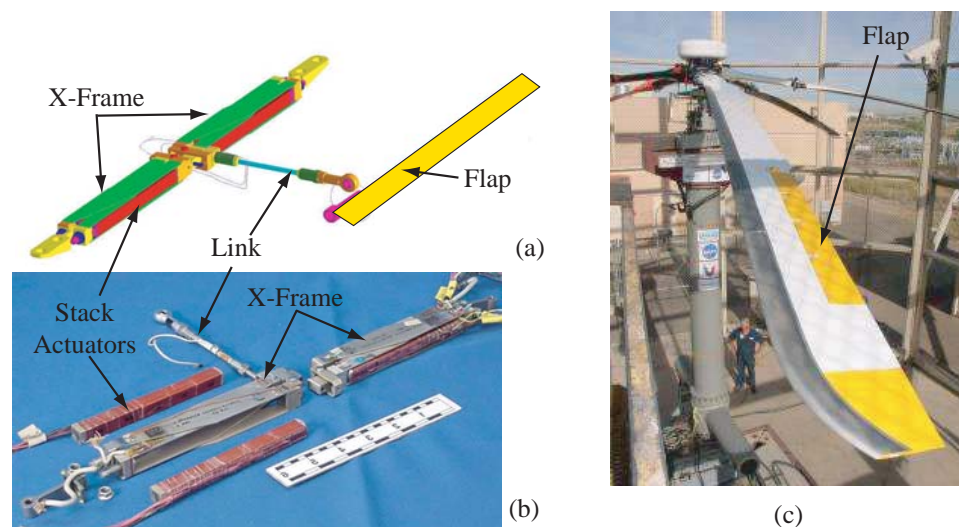


Figure 1: Trailing edge flap using (a) X-Frame (b) hardware concluded (c) whirl tower tests [12]

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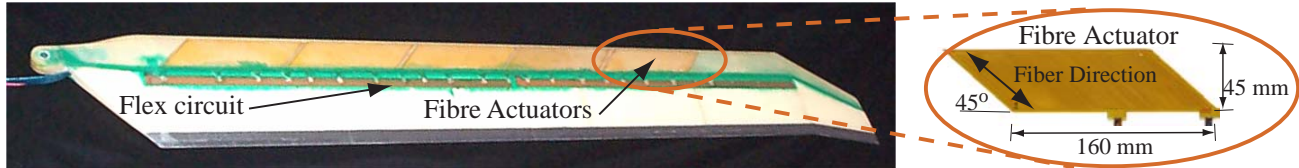


Figure 2: Integral Twist Actuated Rotor Blade and a piezoceramic fibre actuator [15]

2.1.3 Active Acoustic Control of Cabin Noise

Active Structural Acoustic Control (ASAC) is a promising approach to suppress low frequency noise in propeller aircraft or helicopters. This approach is designed to reduce the transmission of noise into the interior before it enters the cabin. In this method, microphones are distributed throughout the cabin to continuously monitor the noise and actuators are attached to the fuselage at strategic locations to modulate the structure response. The controller identifies the dominant frequencies within the cabin using microphone measurements and commands the actuators to counteract the fuselage response due to propeller wake, thereby reducing the noise inside the cabin. Successful experiments were conducted on a full-scale Bombardier Dash-8 turbo-propeller aircraft using bonded piezoceramic elements [19]. The adaptive feed-forward controller implemented in the experiment was able to reduce the interior noise within fuselage subjected to simulated propeller noise. A noise reduction of approximately 28 dB was achieved at the blade passage frequency of 61Hz. Similar ASAC technique has been successfully introduced into commercial aircraft. The ASAC system employed in the Bombardier Q-Series aircraft uses miniature electromechanical shakers as structural actuators as illustrated in Figure 3 [20].

2.2 Shape Memory Alloy

Shape Memory Alloys (SMAs) are other types of active materials currently used for low frequency applications. SMAs have the ability to undergo relatively large reversible deformation in response to the application of heat. However, due to the requirement of heating, the actuation frequency is limited by the time required to heat the material. Therefore, SMA wires or tubes with low thermal mass are used to improve the conductivity that allows efficient resistive heating with electrical current. The original SMA, known as Nitinol, contained compounds of Nickel and Titanium but current alloys include Copper which leads to larger amplitudes (5-8%) and increased stability in the actuation cycle [21]. A variety of SMA based actuators are currently being developed for aerospace applications.

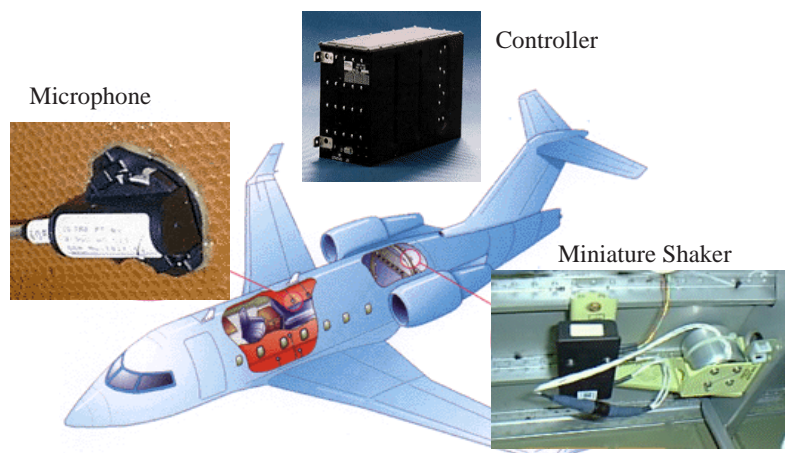


Figure 3: ASAC system implemented in Bombardier Q-series aircraft [20]

2.2.1 Tab for In-Flight Rotor Tracking

An actuator based on SMAs is under development for continuous in-flight tracking of rotor blades. Proper blade tracking is important in helicopters because the vibration increases when the path of each blade tip deviates from the rotating plane. At present, blades are trimmed manually by bending the tracking tab of the blade during major maintenance operations. Adjustments to the tab are performed on the ground and flight tests are conducted to verify the proper tracking. Once the blades are trimmed, the trim tab is not adjusted until the next major maintenance action. The SMA tracking tab improves vibration and noise in helicopters because it enables the rotor to be trimmed continuously. A SMA blade tab was tested to evaluate force, motion and temperature characteristics and the results showed that the actuator met static and dynamic loading requirements for the in-flight blade tracking application [22]. Full-scale flight hardware implementing this concept on a MD-900 rotor blade has successfully concluded whirl tower tests [23].

2.2.2 Variable Twist Blade for Tiltrotor Aircraft

A SMA actuator system is also under development to actively alter the twist distribution on a tiltrotor blade between hover and forward flight. The tiltrotor aircraft have the ability to combine the advantages of hovering flight of a helicopter with high speed forward flight of a fixed-wing aircraft. However, the optimal blade twist and the planform distribution for these two regimes are different. Current tiltrotor blade design represent a compromise between optimum designs of the two flight conditions [24]. Due to the non-optimized blade design, the tiltrotor aircraft not only have degraded performance but also have increased levels of vibration and noise. Recent advances in SMA actuator and advanced composite technologies are being used to optimize tiltrotor blade design for each flight condition in real-time. Preliminary tests show that variation of the blade twist by 6 degree between hover and forward flight improves vibration and noise characteristics as well as aircraft performance [25].

2.3 Magnetorheological and Electrorheological Fluid

Magnetorheological (MR) and Electrorheological (ER) fluids are typically composed of non-conducting oils and varying percentage of particles dispersed randomly throughout the oil substrate that exhibit reversible changes in rheological behaviour in the presence of a magnetic or electrical field, respectively. This change in the fluid viscosity from liquid state to gel-like state has enabled the development of several active damping devices. The ER fluids include fine dielectric particles that align along the electric field to increase the yield stress of the fluid to 2-5kPa within 0.001 seconds [26]. Similarly, MR fluids include iron particles that form a chain in the direction perpendicular to the fluid flow to increase the yield stress to 50-100kPa under 0.01 seconds [26]. Even though MR fluids have slower response time, MR fluids have been more widely used for active damper designs compared to their ER counterpart, since the amount of active fluid required for comparable mechanical damping performance in ER fluid is approximately two orders of magnitude greater than that of a MR device [27]. In addition, MR devices can be operated using common 12-28V power sources and MR fluid is not very sensitive to contaminants [27]. These factors have increased practical application of MR fluid based devices compared to ER fluids.

2.3.1 Seat Vibration Suppression System

A MR fluid based active damping system is currently integrated into vertical suspension seats widely used in vehicles to isolate passengers from whole body vibration and shock [28]. This active system consists of a controllable MR fluid damper, a control computer integrated with a sensor and three-position ride mode switch offering light, medium or firm damping. These active dampers were tested for a range of frequencies, displacements, and input currents. The test results showed that the MR fluid damper was able to provide three

to four times the amount of damping force compared to conventional units [6]. Moreover, without an application of an electric current, the MR fluid unit acts as a passive vibration absorber. Therefore, failure in the active control system does not impair the use of the seat or lead to safety issues. A similar vibration suppression system is very beneficial for helicopter seats. However, ER fluid based systems may provide a better actuator system because the bandwidth of MR fluid is not sufficient for most aircraft applications.

2.3.2 Landing gear vibration suppression

The continuously controllable damping characteristics and the wide control bandwidth of ER or MR fluids offer the flexibility to develop adaptive landing gear systems as shown in Figure 4(b). During touchdown, an aircraft is exposed to short duration impulsive impact that may lead to structural damage and high dynamic stresses in the airframe as well as crew and passenger discomfort. Passive devices currently used are adjusted to the most frequently expected impact loads. However, these passive shock absorbers do not perform well due to the high variation in the impact conditions at each landing. Recently, an active shock absorber system illustrated in Figure 4(a) based on the ER/MR fluid is being implemented for off-road vehicles such as the US Army's High-Mobility Multi-purpose Wheeled Vehicle (HMMWV) or heavy vehicles such as trucks [6]. A similar system with the ability to optimize the damping characteristic in the landing gear system is able to attenuate the impact loads transmitted to the fuselage significantly [29]. The simulations have shown that acceleration and displacements were significantly attenuated by MR/ER fluid based landing gear systems regardless of parameter variations such as vehicle mass, viscous damping, impact speed etc. Implementation of this active materials based landing gear system will be experimentally tested in order to compare the performance with existing systems [29].

3.0 SMART SPRING: A NOVEL ADAPTIVE VIBRATION CONTROL APPROACH

Most piezoceramic actuator based active vibration control approaches discussed previously attempt to suppress vibrations by directly opposing excitation vibratory loads. However, successful implementation of these approaches has been hindered by the electromechanical limitations of piezoceramic actuators. In contrast to other approaches, the Smart Spring is a patented concept capable of suppressing mechanical vibration indirectly by using piezoceramic stacked actuators [30]. The Smart Spring device is designed to adaptively vary structural impedance properties, namely, stiffness and damping at strategic locations of a structure to suppress vibratory displacements and/or transmitted reaction force. The viability of modifying structural impedance properties, such as stiffness, damping and effective mass, to suppress mechanical vibration has been analytically demonstrated previously [31]. The Smart Spring is a device that enables structural impedance control to suppress vibration while overcoming limitations of other approaches.

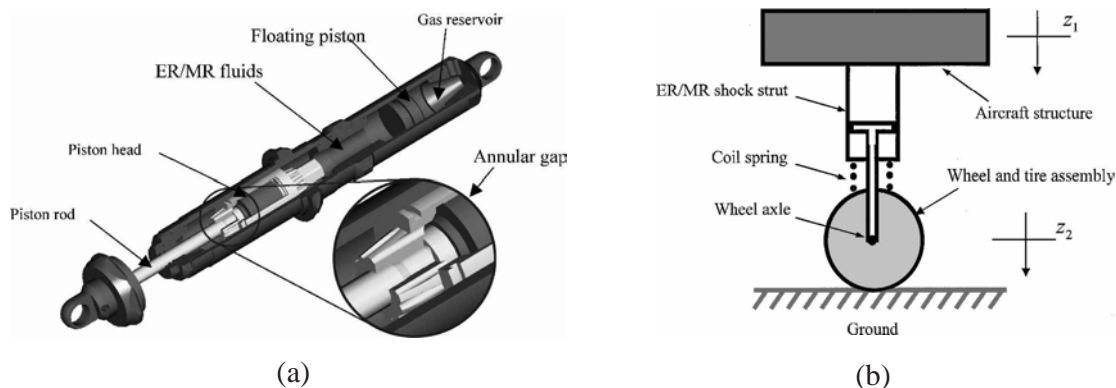


Figure 4: (a) MR fluid shock absorber and (c) active landing gear implementation

3.1 Smart Spring Concept

The Smart Spring mechanism, as shown in the conceptual drawing in Figure 5(a), is placed in the load transmission path between the vibratory source and the target section. The spring designated by K is the primary load-carrying path and the active spring designated by $K(t)$, attached to the piezoelectric stack actuator, operates in a sleeve attached to the structure. When voltage is applied to the actuator, a normal force $N(t)$ is generated between the actuator and the sleeve to engage the active spring $K(t)$ with the structure. The dynamic friction force $F(t)$ applied to the sleeve is continuously controlled by the external voltage stimulus to the actuator. As a result, the voltage applied to the piezoelectric actuator is able to preferentially vary the combinations of stiffness and damping as shown by Figure 5(b). This mechanism exploits the large stiffness, high bandwidth and low displacement capability of stacked piezoelectric actuators. Details of the Smart Spring concept and results of extensive characterization tests have been previously published [32]. A real-time controller was implemented to control piezoelectric actuator voltage in order to vary the stiffness and damping in an adaptive manner at high frequencies to suppress both vibratory displacement and/or reaction forces.

3.2 Advantages

The primary advantage of the Smart Spring concept is that the piezoceramic actuator is used to suppress vibration in an indirect manner. The actuator controllably engages the active spring to adaptively vary the effective structural impedance properties at critical locations. It is the change of the flexural characteristics that controls the dynamic response of the structure. Therefore, compared to other piezoelectric actuator based approaches, the Smart Spring system does not rely on the piezoelectric actuators to achieve high stroke and force simultaneously. Rather, the device only requires the actuators to produce micro displacements to engage the active spring with the structure. Therefore, complex displacement amplification mechanisms are not required. Furthermore, the stacked piezoelectric actuators are able to achieve sufficient forces with less than 100V. The feasibility of the system implementation is thus enhanced due to the use of low driving voltage. The hardware components of a Smart Spring system designed as an axial vibration suppression mount is shown in Figure 6(a). The assembled system as seen in Figure 6(b) has a small footprint and the whole system is scalable to be used in a variety of mechanical vibration control application.

3.3 Potential Application of the Smart Spring Concept

The Smart Spring is a versatile concept that can be easily implemented in various mechanical vibration and structure-borne noise control applications. The basic concept can be implemented to control different

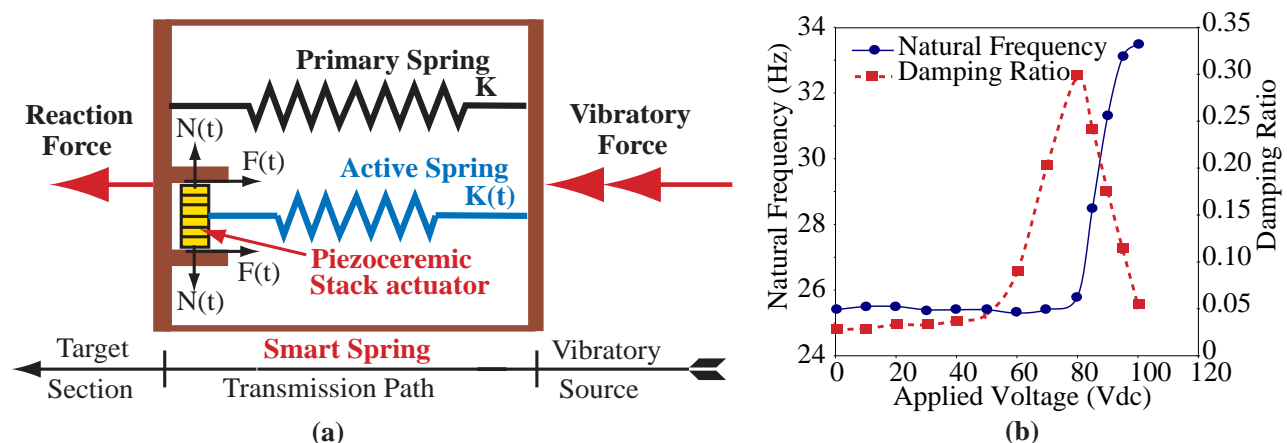


Figure 5: The Smart Spring (a) vibration control concept with (b) active variability of properties

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vibratory loads such as axial, bending, torsion or a combination of these loads. The high frequency operation, low voltage requirement and small footprint of the device makes the Smart Spring a suitable solution for vibration and noise issues in helicopters, aircraft, ships or land vehicles. The control objective of the Smart Spring system can be selected based on the application to reduce vibratory displacement, mitigate transmission of the reaction force, or suppress both the displacement and transmission load. For each application, optimized design parameters of the Smart Spring, particularly the characteristics of the primary spring and the active spring, must be carefully selected in order to improve performance, ensure safety, and guarantee reliability.

3.3.1 Adaptive Seat Vibration Suppression System

The Smart Spring system can be implemented as an adaptive mount to suppress vibration displacement in a base excitation system such as a vehicle seat. A Smart Spring based adaptive seat mount system inserted at the interface between the seat and the vehicle, as shown in Figure 7(a), is able to provide significant reduction in the vibration transmitted to the seated person. For example, such an adaptive mount system in helicopter seats is capable of mitigating vibration caused long-term health issues and also improving the effectiveness of the aircrew. A real-time adaptive system is essential to provide the required vibration suppression performance of seats under highly varying conditions that exists in vehicle operation, in particular, helicopters and propeller aircraft. Such a system is very beneficial because vibration induced health issues are amplified by the increase in helmet weight due to addition of night vision goggles, heads-up displays, etc. The real-time controller will optimize the vibration suppression performance in accordance to pilot weight, flight condition, aircraft configuration, etc. The characteristics such as small foot print and low voltage operation will enable Smart Spring based adaptive seat mounts to retrofit current vehicles.

3.3.2 Adaptive Engine Mount System

The Smart Spring based adaptive engine or gearbox mount can be designed to suppress the transmission of vibratory loads from the source to the rest of the vehicle structure as illustrated in Figure 7(b). The adaptive mount placed in the vibration load path will mitigate mechanical vibration as well as structure borne noise generated by the vibration of the structure. For helicopters, one of the primary sources of noise originates from the vibration of the main rotor drive and the gearbox assembly. The vibrations from gear meshing tones are primarily transmitted through supporting struts to the airframe which then radiate into the cabin. This transmission noise is usually in the range of 500Hz to 1500Hz. Reduction of the gear box vibration will not only extend the expected life of expensive vehicle components but also improve the noise and vibration environment for passengers, which is known to cause annoyance, fatigue and other physiological issues. The piezoceramic actuators will be able to achieve the required bandwidth and the adaptability of the system will

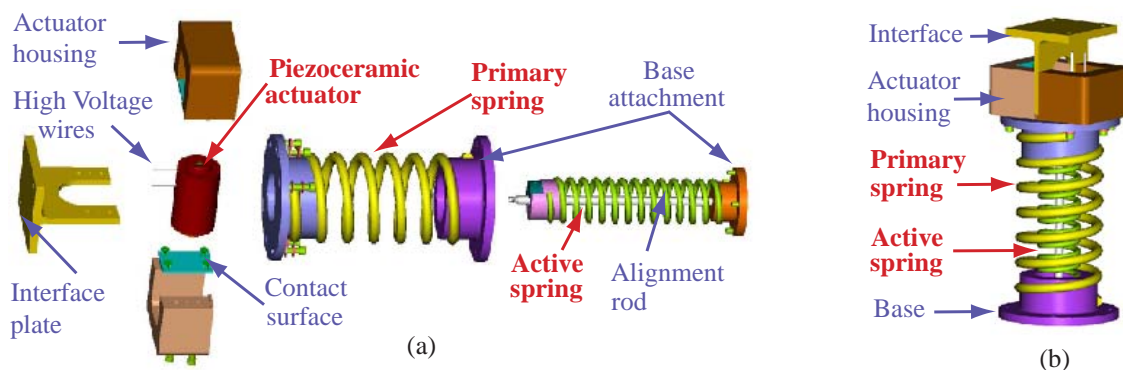


Figure 6: The Smart Spring Hardware (a) exploded and (b) assembled view

be able to react to unpredicted vibration variations due to changes in vehicle configuration, operating conditions or mission.

3.3.3 Rotor Vibration Control

One of the most demanding potential applications for the Smart Spring system is the control of rotor vibration in helicopters. In this application, the Smart Spring is used to suppress both the vibratory displacement of a helicopter blade as well as the transmission of vibratory loads from the blade to the rotor hub. Such an on-blade control system can reduce vibration as well as noise in rotorcraft significantly. The Smart Spring device can be installed at the root of a helicopter blade, as illustrated in Figure 7(c), to control vibration generated by unsteady aerodynamics in the rotor [33]. Controlling the Smart Spring using an adaptive algorithm allows on-line tracking of blade vibratory frequency variations in order to achieve the greatest suppression performance.

3.4 Adaptive Vibration Control Demonstration

To demonstrate the performance of the Smart Spring concept for the rotor blade application, a 1.3m helicopter blade section with a 0.3m chord was attached to the Smart Spring proof-of-concept hardware in a cantilever configuration. The proof-of-concept hardware demonstrated that the Smart Spring system was capable of varying stiffness and damping properties in a controlled manner [34]. In order to verify the vibration control capability, the Smart Spring was tested in a wind tunnel under unsteady aerodynamic loads, designed to simulate a representative aerodynamic environment in helicopter rotor blades. A closed-loop adaptive controller was used to achieve vibration suppression at multiple frequencies. The controller applied appropriate voltage to the stacked piezoelectric actuators of the Smart Spring in order to adaptively vary the stiffness and damping to suppress blade vibration and transmitted force.

The wind tunnel tests were conducted in the low speed wind tunnel facility at the Institute for Aerospace Research of the National Research Council Canada. The fundamental vibratory frequency depended on the wind speed and the dimension of the square tube installed upstream from the leading edge of the blade to generate vortices to excite the blade. Due to the unsteady nature of the aerodynamics, the vortex shedding frequency varied randomly by $\pm 10\%$ and the amplitude of the aerodynamic load was unsteady and random as seen in Figure 8(a) for a 13 m/s wind speed. The above wind speed produced a vibratory mean frequency of 12.7Hz, which is near the natural frequency of 15.3Hz for the blade and Smart Spring assembly. Frequency spectrum analyses of the blade root displacement are shown in Figure 8(b) for adaptive control and no control test conditions at the 13m/s wind speed. The vibratory displacement at the blade root with the adaptive controller off was 0.14mm. Once the adaptive controller was activated, the vibration amplitude was reduced by 27.3dB to 0.03mm without a significant variation in the response frequency. In addition, the reaction load

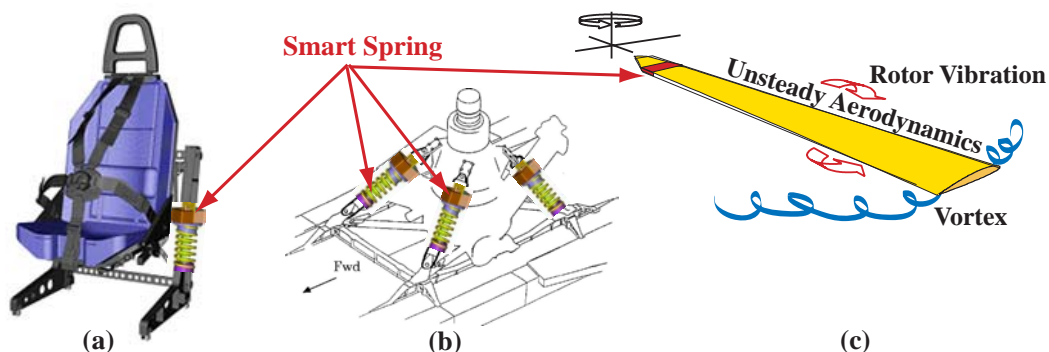


Figure 7: Potential Applications for Smart Spring Concept

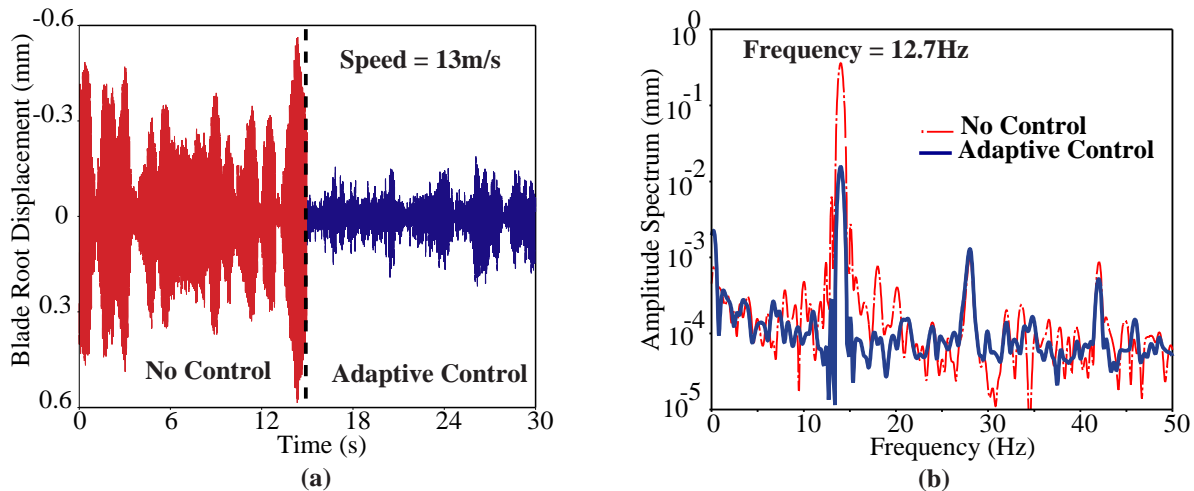


Figure 8: (a) unsteady excitation and (b) vibration suppression results from wind tunnel test

of the blade root showed a reduction of 9.6dB. The test results demonstrated that the Smart Spring system can be successfully implemented in a demanding unsteady excitation environment, such as the helicopter rotor, to suppress both the blade vibrations as well as the hub reaction forces [35].

5.0 SUMMARY

It is important to reduce undesired vibration and noise inherent in transport and combat vehicles in order to improve habitability, effectiveness, and safety as well as long-term physiological effects on passengers and aircrew. In contrast to passive approaches, active approaches can be used in an effective manner to suppress mechanical vibration and low frequency noise significantly, over a broadband of frequencies. Various smart structures techniques using active materials have been studied for vibration and noise suppression applications, particularly for helicopters and propeller aircraft due to their inherently high levels of vibration and noise. These include PZT based active helicopter blades, SMA based propeller blades, and MR/ER fluids based dampers. Although some of these techniques have shown significant suppression performance, their implementation in full-scale vehicles been hindered by the electromechanical limitations of active materials.

The Smart Spring is a novel approach designed to control combinations of impedance properties of a structure, such as the stiffness, damping, and effective mass. It uses stacked piezoceramic actuators to adaptively vary these structural impedance characteristics at strategic locations to suppress mechanical vibration. The Smart Spring is a promising approach for many mechanical applications, specifically for vehicle vibration and noise control. An adaptive mount system based on the Smart Spring can be easily implemented to reduce vibratory displacements on vehicles seats, or mitigate vibratory loads transmitted from the engine or gearbox, or suppress helicopter rotor vibration. The Smart Spring is a unique concept that overcomes many of the difficulties encountered with other piezoceramic based active vibration control approaches. Extensive experimentation using mechanical shaker tests demonstrated the ability of the Smart Spring to control impedance properties in an adaptive manner to suppress vibration. The wind tunnel tests demonstrated that the Smart Spring is capable of suppressing both the vibratory displacement as well as the reaction force transmitted under unsteady excitation conditions.

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Detailed Analysis or Short Description of the AVT-110 contributions and Question/Reply

The Questions/Answers listed in the next paragraphs (table) are limited to the written discussion forms received by the Technical Evaluator. The answers were normally given by the first mentioned author-speaker.

P16 D.G. Zimcik, V.K. Wickramasinghe, Y. Chen ‘A Novel Adaptive Structural Impedance Control Approach to Suppress Aircraft Vibration and Noise’, (NRC, CA)

The author described the adaptive approach based on the use of smart structures (PZT piezo-ceramic, SMA Shape Memory Alloy and MR Magneto-rheological Fluid by the design of devices (smart spring for controlling the blade vibration of an helicopter) allowing to reduce the level of vibration by 5 to 12 dB, concluding on the promising applications of these kinds of structure.

Discussor’s name: M-C Tse

Q. (1) What do you mean by “broadband frequency”? Is it one frequency at a time, while the device can cover a wide range of frequencies? (2) How good is the vortex simulation by the square tube?

R. (1) Results of test of the Smart Spring have shown vibration amplitude reduction over a very wide (broadband) frequency- range. However the Smart Spring has much greater capability to reduce narrow band vibration. Specifically the Smart Spring can be controlled by an adaptive (active) control law and it can respond to wide changes in the centre frequency of such narrow band frequency bands. This of course is the power of an adaptive active system.

(2) The phenomenon of vortex shedding from a square tube is well documented. The square tube approach provided a time varying vortex stream to impact the airfoil on opposite sides to generate an oscillatory driving force

Discussor’s name: J. Vantomme

Q. PZT and SMA are well developed in research. What is the position of the “Smart Spring” concept in the R&D area? What about the future of PZT, SMA, SS – developments and R&D strategy?

R. As noted in the presentation, the concept has been demonstrated through test of proof-of-concept hardware. Specific work is underway to apply this concept to address problems experienced in ‘real-life’ hardware. As also noted in the presentation, there are a number of limitations with PZT, SMA, etc. However, these materials have played their roles in the development of smart structures systems, but new approaches will be needed to overcome these problems / limitations. The Smart Spring is a novel approach to this end.

Discussor’s name: K. Kowalczyk

Q. What kinds of design criteria are you using to decide whether you are using feedback or feed-forward control approach?

R. We have investigated both feedback and feed-forward control laws to evaluate both performance and adaptability to change with changing input conditions. In addition to general vibration reduction, results, influencing factors such as speed of response, bandwidth and centre frequency calculation and evaluation are important deciding factors in the overall selection. It is not expected that either feedback or feed-forward will be the best choice for all applications but this choice will vary depending on the above factors.

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Approach to Suppress Aircraft Vibration and Noise**

